A FREQUENCY MODULATED LASER COMMUNICATIONS SYSTEM

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THESIS

A Frequency Modulated Laser Communications System

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ABSTRACT

The design of a system for point-to-point voice communications using a frequency modulated diode laser as the transmitter is presented. Theories are discussed for the Ga-As semiconductor laser, the laser pulse circuits, the p-i-n silicon photodiode detector, and the frequency demodulator. Designs of the elements of the system and some experimental results are presented. Operation of a complete system is discussed.

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I. INTRODUCTION

A. OBJECTIVE

It was proposed to design and construct a laser communication system for voice transmission which utilized laser diodes operated in a pulsed mode and which used integrated circuits to minimize size, to provide transceiver capabilities and to permit portability. It was further hoped to incorporate the system into a secure communications network.

B. BACKGROUND

The first working laser was built in mid-1960. This was the beginning of a new field of scientific endeavor. Although the laser was, and is, of interest to all the traditional scientific disciplines for theoretical applications, the interest in lasers is universal.

The proposed and realized uses of lasers are well documented. As a scientific tool its role has been well established [Ref. 1]. It has been used to further the study of quantum electronics as well as being used as an investigative tool in many areas of physics, electrical engineering, and other scientific disciplines.

The laser's utilization in industry has also been established [Ref. 2]. It is used for surveying, welding, cutting cloth to very precise measurements, for medicine as a surgical instrument, and even for an erasor which vaporizes ink from a paper.

The use as a carrier wave for a communications system may one day overshadow the present applications. "There are probably more physicists and engineers working on the problem of adapting the laser for use in communications than on any single project in the field of laser applications."

[Ref. 3]. Because the capacity for a channel to transmit information is proportional to the width of its band of frequencies, the laser operating in the visible and infrared region of the electromagnetic spectrum should be able to carry much more information than can be presently carried by radio frequency systems. Additionally, the directionality of the beam and the frequency of operation permit operation in an uncrowded region of the electromagnetic spectrum.

Much of this interest has been centered on long-range communications. [Ref. 4 and 5]. This interest has resulted from the coherence that is a property of laser light. This coherence can be utilized to produce a highly collimated beam which can be sent great distances. Unfortunately, the earth's atmosphere can perturb this beam thereby causing research to be directed toward deep space communications where atmospheric effects would not be present.

In 1962, the first of the semiconductor laser diodes appeared. The advantages of these diodes over solid-state (crystal) or gas lasers are: inexpensive price, ruggedness, small size, ease of modulation and much lower operating voltages. These features make systems composed of these diodes useful for portable line-of-sight communications which require little maintenance. A limitation, however, is that the diodes' peak power output is on the order of a few watts, thereby limiting the range, especially for deep space applications.

Another limitation of the diodes that are presently widely available is that they can be operated only in a pulse mode at room temperature. There have been some operated at room temperature in a continuous wave (CW) mode, but these are presently in the experimental stage and require elaborate heat sinks. (The temperature limitations are discussed in the

section on System Design.) This limitation forces the engineer to work with pulse modulation systems or with transmitting digital information. In the latter application, the laser could be used as a link between computer terminals to transmit information at the speed of light by means of fiber optics.

Operation of these diodes at infrared wavelengths leads to a system that is relatively secure to interception as the device is short-ranged and can be readily used for point-to-point communications. Further improvement to security can be obtained by adding simple optics to the system thus forming a very directive beam.

Commercially, a few systems have been built utilizing the gallium arsenide (GaAs) semiconductor laser diode as the transmitter for the system. Santa Barbara Research Corporation has marketed a transceiver using pulse frequency modulation for single channel voice [Ref. 6 and 7]. A carrier frequency of 6KHZ with a modulation deviation of ±600HZ was used to pass a 100HZ to 2300HZ bandwidth of audio. The system has a peak power output of 10 watts. Two output beamwidths can be used. A 3^{o} beam provides a range of 2.5 miles while a 2^{o} beam gives 4.0 miles range in a minimum visibility of 10 miles. The system is mounted in a binocular arrangement that is hand-held to provide the same ease and dexterity of use found in ordinary binoculars.

Another system was designed by Holobeam, Inc. and was contracted by the United States Navy for use in ship-to-ship communications during refueling [Ref. 8]. Pulse position modulation was used as the modulation scheme. This type of modulation was believed to have better fidelity and security than a frequency modulated system. The high fidelity was due to the conversion of the analog signal into pulse positions in time without an

analog-to-digital converter while reconstruction was made without a digital-to-analog converter. Additionally, variations in laser output power would not affect the fidelity of the received signal. In this system, the Ga-As diode was also used to enhance security due to the infrared emission of the diode. The original design had a maximum range of 10 miles which was later reduced to 250 feet to meet the Navy's specifications. The optics were mounted on a helmet with the electronics and power pack fitted to a belt.

A third system was designed by the Navy Electronics Laboratory Center at San Diego for use as a telephone circuit. The system was designed for use in internal shipboard communications using fiber optics as transmission lines. Pulse position modulation was used as the modulation scheme. An important difference from the other two systems described above was the use of a light-emitting diode (LED) as the light source. The LED operates at a lower voltage than the laser diode, is able to be pulsed at a higher frequency, and is used in multiplexing systems so that several channels can be transmitted, thus permitting use with fiber optics and telephone circuits.

II. THE FREQUENCY MODULATED LASER SYSTEM

A. PROPOSED OPERATION

Signal transmission was to be accomplished by pulsing a GaAs laser diode at a reference (carrier) pulse repetition rate of 7 KHZ. The pulse repetition rate was then to be frequency modulated by voice signal inputs of 300-3000 HZ bandwidth with the modulation deviation not to exceed $\pm$1350 HZ. Because the laser can be pulsed at a rate equal to the frequency of trigger pulses applied to the pulsing network, it was decided that the most direct form of modulation was to apply the frequency modulated (FM) signal to the pulser as the trigger pulses. The FM signal would be generated by a voltage-controlled ascillator (VCO). The output light pulses from the laser were to be detected (received) by a photodiode, amplified, and fed to a FM demodulator. The demodulated signal was to be filtered, amplified and outputted in the form of audio from a speaker.

B. TRANSMITTER DESCRIPTION

The transmitter circuitry converts the audio signal into a series of coherent light output pulses. A block diagram of the transmitter is shown in Figure 1. The microphone converts the speech pressure waves into an audio signal. The preamplifier provides the necessary amplification to the microphone output while a bandpass filter permits only some audio frequencies (300-3000 HZ) to be transmitted by the system.

An attenuator prevents the audio signal applied to the VCO from exceeding a voltage that would give a modulation greater than $\pm$1350 HZ. The VCO freeruns at the carrier repetition rate of 7 KHZ. The square wave out-

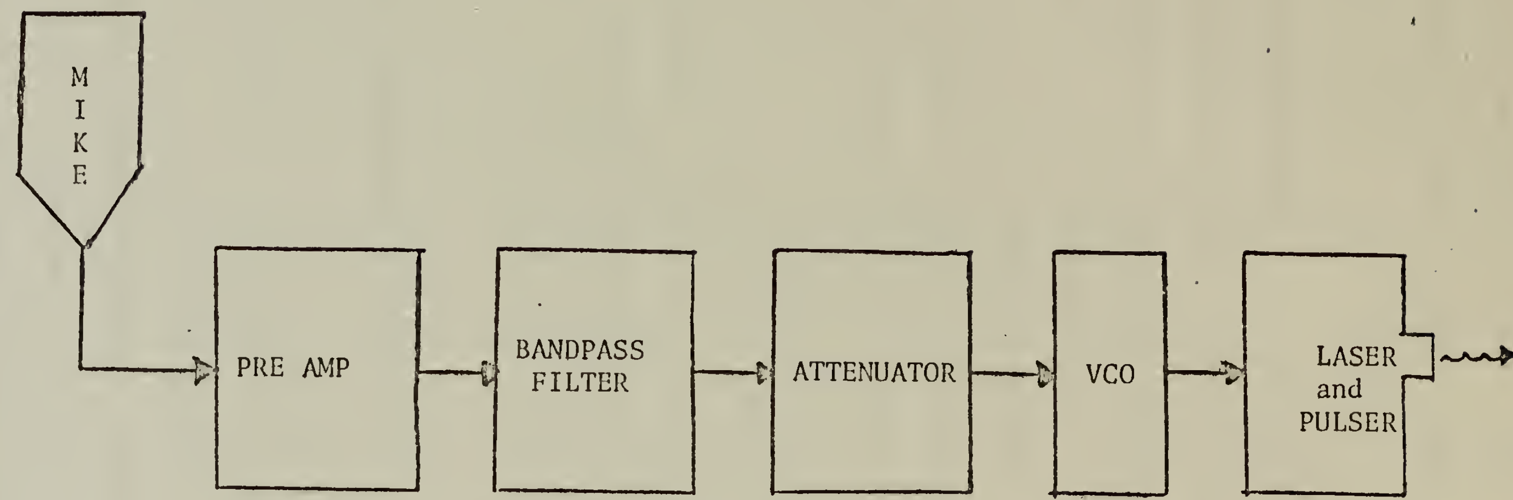


FIGURE 1: TRANSMITTER BLOCK DIAGRAM

put of the VCO, modulated about the 7 KHZ carrier, modulates the laser's pulsing circuitry so that the laser output is also frequency modulated about 7 KHZ.

C. RECEIVER DESCRIPTION

The block diagram of the receiver is shown in Figure 2. The principal element of the receiver is the photodiode detector. It responds to the transmitted laser light and provides electrical pulses corresponding to the input light pulses. These pulses are then amplified by an operational amplifier (op amp) and fed to an FM demodulator. The demodulator is a phase-locked loop (PLL) circuit which has an internally-generated frequency of 7 KHZ. The frequency difference between the input signal and the reference signal is detected and a voltage is generated proportional to this difference. (The PLL will be described in detail in a following section.) This voltage is the same voltage used to modulate the transmitter VCO. The voltage is then filtered, amplified, and is used to drive a speaker.

D. THE GA-AS SEMICONDUCTOR LASER DIODE

The laser diode used as the transmitter in the system was a heterostructure injection (heterojunction) laser. The diode is formed of three distinct layers: n-type gallium arsenide, p-type gallium arsenide, and p-type gallium aluminum arsenide. The structure is shown in Figure 3. A heterojunction is defined as the junction formed between two semiconductors having different energy band gaps [Ref. 9]. The heterojunction in the Ga-As diode is formed at the interface of the p-type gallium arsenide and the p-type gallium aluminum arsenide. The principle of operation of the diode can be studied by consideration of the diffused homojunction (junction of semiconductor materials with the same energy band gaps) semiconductor laser.

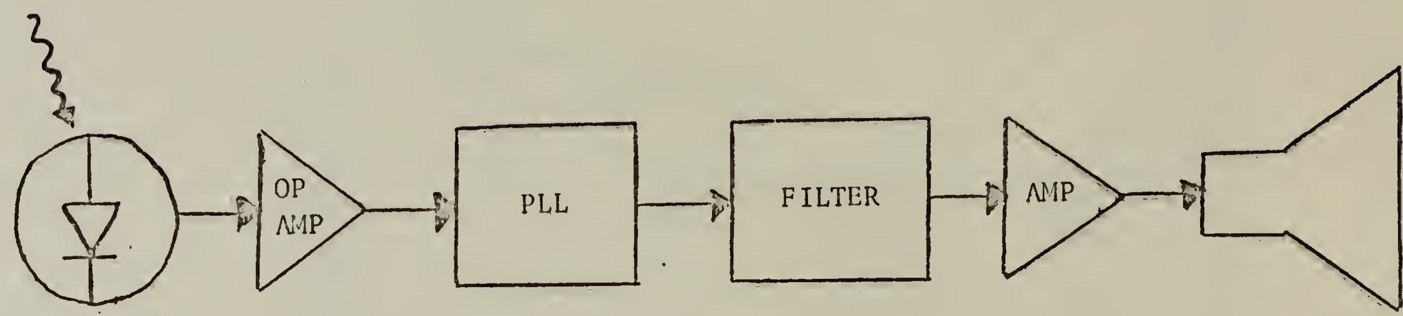


FIGURE 2: RECEIVER BLOCK DIAGRAM

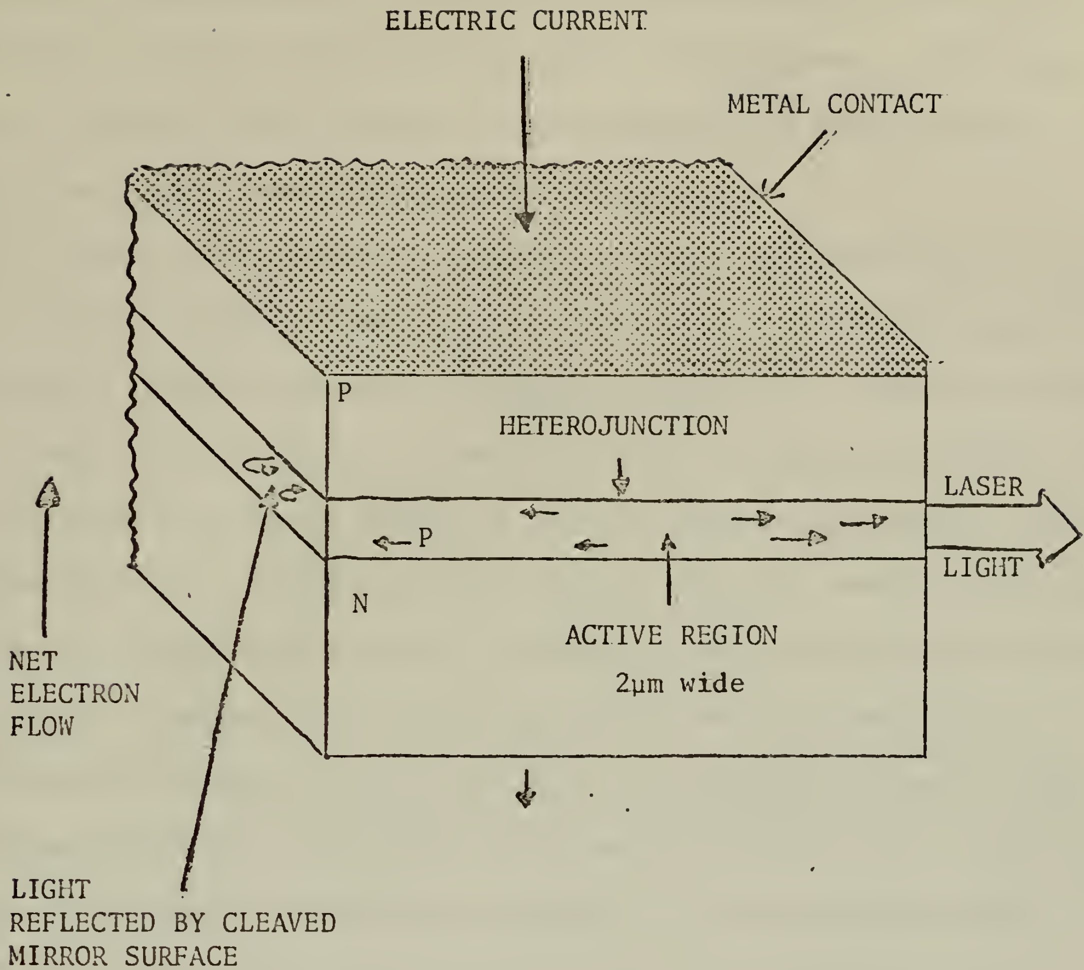


FIGURE 3: THE SINGLE HEREROJUNCTION Ga-As SEMICONDUCTOR LASER DIODE (AFTER REF. 11)

The junctions of all semiconductors will emit some radiation if the devices are forward biased. The radiation results from the release of energy when electrons and holes recombine in the junction. This form of emission is accomplished by a different mechanism than the emission of the solid state (ruby, Nd-YAG) or gas (CO_2, He-Ne) lasers. With these lasers, emission is the result of transitions between electronic or vibrational energy levels of homogeneous materials.

The lowest energy state of a system is called the ground level. Any other level is called an excited level. A system not in its ground state can exhibit either spontaneous or stimulated emission. A spontaneous emission results from a radiative transition between a higher and a lower energy level without an external stimulus. This emission is incoherent. When an external stimulus is used to produce a transition, the result is stimulated emission characterized by coherent radiation. This is called light amplification by stimulated emission of radiation, hence the word laser.

A necessary condition for laser action is population inversion, the condition of a higher energy level being more populated than a lower one. This is an unnatural state for most materials as they want to remain in a state of lowest energy (thermal equilibrium). Transitions occur from the higher to lower energy levels with the release of energy in the form of radiation, as the system tries to re-establish equilibrium. This discussion applies to all lasing materials whether gas, crystal, or semiconductor. The difference between them is the means of obtaining the population inversion.

The gas and crystal lasers' population inversions result from excitations to higher levels within the materials themselves. The semiconductor laser uses materials of electronically dissimilar energy structures where

the dissimilarity results from gaps of forbidden energy, characteristic of semiconductor materials. The inversion occurs at the junction of the materials when a bias voltage is applied to the device.

In the doped semiconductors, donor impurities produce an excess number of electrons in the conduction band, thus forming an n-type semiconductor. Similarly, the material can be doped with acceptor impurities causing an excess of holes in the valence band to form a p-type semiconductor. The laser diode is a Ga-As wafer heavily doped with Tellurium (donor) and Zinc (acceptor) to form a junction. The equilibrium band diagram before a forward bias is applied is shown in Figure 4A. The Fermi level, $\emptyset$, is below the top of the valence band in the p-region and above the conduction band in the n-region. This is because of the heavy doping; i.e., the material is "degenerately doped." The application of a forward bias across the junction produces a region of population inversion at the junction. The equilibrium band diagram for this condition is shown in Figure 4B.

In the inversion region more quanta are emitted than absorbed in radiative transitions between conduction and valence bands. The condition for population inversion in a junction laser requires that the forward bias voltage applied across the junction must be large enough so that eV is larger than the energy of the emitted radiation, $h\nu$ [Ref. 10]. At room temperature, the energy of emission is about 1.37 electron volts for a wavelength of 9050 Å.

There is a current threshold associated with internal losses that must be overcome before lasing action begins. This is shown in Figure 5. For the Ga-As laser, the threshold current density at room temperature is about 41,000 $\mathring{A}/cm^2$ [Ref. 10]. Below this threshold the diode will emit a

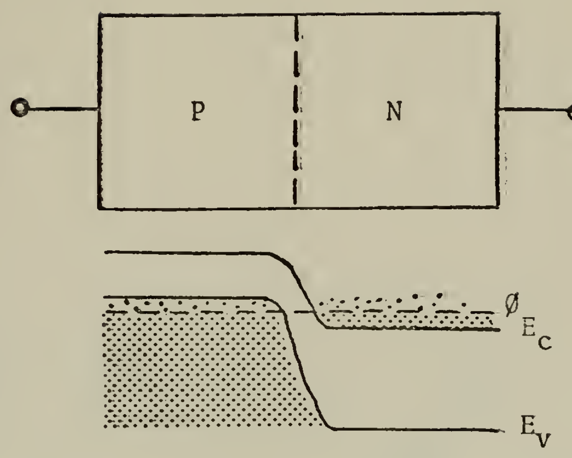


FIGURE 4A: DIODE ELECTRON BAND DIAGRAM BEFORE FORWARD BIAS APPLIED (AFTER REF. 10)

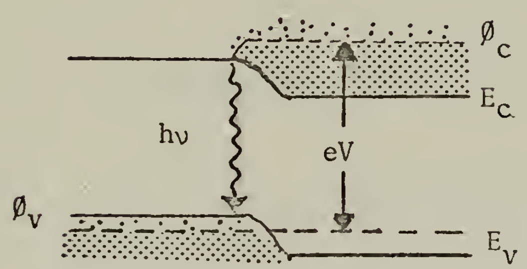


FIGURE 4B: DIODE ELECTRON BAND DIAGRAM AFTER FORWARD BIAS APPLIED (AFTER REF.. 10)

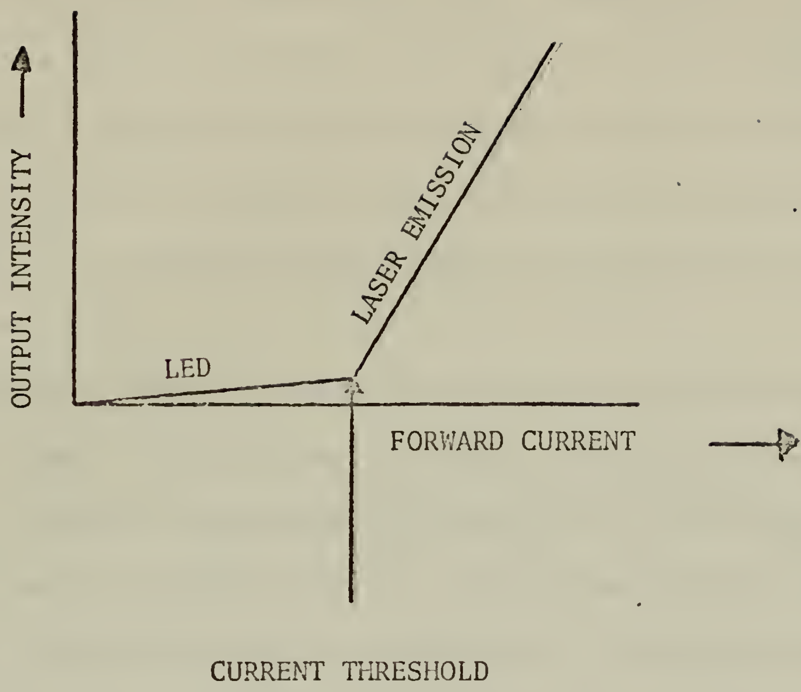


FIGURE 5: LASER CURRENT THRESHOLD (AFTER REF. 16)

luminescence that is typical of the light-emitting diode (LED). The width of this LED spectrum, though narrow when compared to the spectra of most luminescent semiconductors, is much wider than the width of the laser line. A comparison of the two spectra versus emission intensity is shown in Figure 6. Although Figure 6 was obtained for the InAs diode, it is typical of semiconductor lasers.

The forward bias produces a rapid rise in the junction temperature, resulting in a large amount of heat which must be dissipated. To prevent destruction of the diode by this heat, the laser is usually operated in a pulse mode. Early semiconductor lasers often had to be run at cryogenic temperatures to obtain CW operation but by the use of elaborate heat sinks made of diamond it is possible today to operate in a CW mode at room temperatures [Ref. 11].

The heterojunction laser is a more efficient laser than the homojunction laser described above. The p-p junction serves to confine the injected electrons and to reduce reabsorption by limiting the active region to a narrow width. Thus, the device operates with considerably less current as the threshold is reduced and the power efficiency is correspondingly increased. The threshold current density that is needed to produce the lasing action depends upon the width of the active region [Ref. 11]. For the single heterojunction this region is about 2μm wide and for the double heterojunction about .2μm wide. The homojunction laser has an active region from 2 to 5μm.

These diodes can be easily modulated by controlling the excitation current. This is advantageous since no external modulation elements are required. With the commercial pulser used in the system, the modulation was supplied as a trigger voltage. This trigger voltage applied to the pulser produces a current pulse that is the same frequency as the trigger

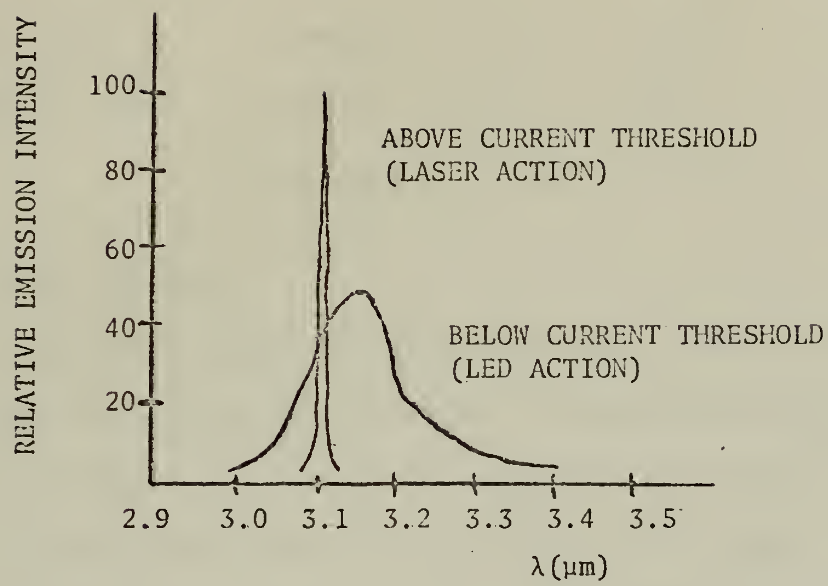


FIGURE 6: SPECTRUM WIDTH COMPARISON OF InAs DIODE (AFTER REF. 10)

pulse. Thus, direct modulation of the laser is obtained and the resulting laserlight is a communications signal.

In the construction of the diode, the ends of the crystal are cleaved and mirrored so that parallel planes are produced which enhance the lasing action. This is noted in Figure 3. The specifications of the diode used in the system are given in Table 1:

At 25^{o} C	Min.	Typical	Max.
Peak power	8 W	12 W	
Threshold current	10 AMP	15 AMP	22 AMP
Pulse width			200×10^{-9} sec.
Wave length	8960 Å	9050 Å	9100 Å
Spectral width	20 Å	25 Å	45 Å

Table 1

E. LASER PULSE CIRCUITS

Pulse laser diodes require narrow, high-current pulses with fast rise and fall times with nominal pulse widths of 130 nanoseconds and rise/fall times of 50 nanoseconds. Current below threshold heats the laser, hence fast rise and fall times result in less heating of the diodes. Current undershoot must also be minimized, as the diodes can tolerate only a very small value of reverse voltage. Therefore, care must be taken to properly design the pulsing circuits.

A typical pulsing circuit is usually a silicon-controlled rectifier (SCR) circuit. The SCR is used as an off-to-on switch and does not shape or turn off the current waveform [Ref. 12]. The circuit generates the desired pulses by discharging a capacitor through the SCR and laser. The circuit consists of three basic sections: (1) the discharge circuit, (2) the charging circuit, and (3) the trigger circuit.

The most important section is the discharge circuit, as it generates the current pulse [Ref. 12]. The configuration of the pulse power supply is shown in Figure 7. The current pulse is generated by the discharge of the storage capacitor C through the SCR and the laser. The rise time is determined by the SCR while the value of C and the total resistance of the discharge circuit determine the fall time. Short pulse widths provide less time for the SCR to turn on; therefore, the SCR impedance is higher and more voltage is required to generate the same current than for longer pulse widths.

The SCR usually reaches its maximum anode current in about one micro-second. During this time the anode to cathode impedance drops from infinity (open circuit) to a fraction of an ohm. Laser pulse supplies provide an anode current pulse of less than a microsecond's duration. Thus, it ceases before the SCR has completely turned on. The anode-to-cathode impedance is about 1 to 10 ohms during this time. The SCR is thus chosen on forward-blocking voltages and current rise times.

The second basic section, the charging circuit (see Figure 7), charges the capacitor to the supply voltage during the time interval between laser current pulses and isolates the supply voltage from the discharge circuit.

The most basic charging circuit is a resistor connected between the high voltage supply and the SCR. The resistor limits the current to a value less than the SCR holding current and determines the charging time of C. Peak current in the discharge circuit is controlled by varying the supply voltage.

The third section of the pulser is the trigger circuit. The trigger circuit must provide a fast-rising current pulse with an amplitude equal to at least five times the minimum triggering current required for the SCR [Ref. 12].

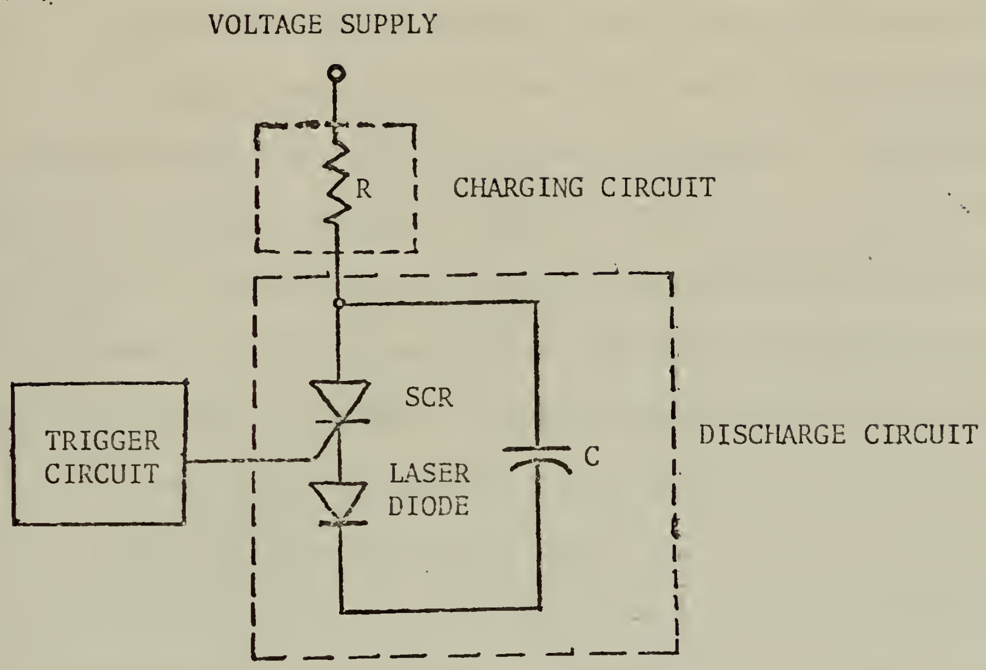


FIGURE 7: LASER PULSE POWER SUPPLY (AFTER REF. 12)

indicated in Figure 8. If the pair is produced in the vicinity of a p-n junction, the electric field across the junction will separate the two carriers to give a photovoltage. This process is called the photovoltaic effect [Ref. 13]. The conversion efficiency of the device is measured by the number of carriers produced per incident photon. The more pairs produced, the greater the efficiency. The only requirement of the detector is that the incident photons produce electron-hole pairs; therefore, only intrinsic semiconductor materials can be used [Ref. 13].

The photodiode construction is shown in Figure 8. The structure is produced by diffusion through an SiO_2 mask which also protects the surface. A gold contact is deposited only around the perimeter of the p-layer, as gold is opaque to infrared radiation. The photon absorbed by the silicon, which is the intrinsic material, produces the required electron-hole pair. For best conversion efficiency, the p-layer should be as thin as possible and the i-layer as thick as possible [Ref. 14].

The equivalent circuit of the photodiode is shown in Figure 9. The current resulting from the incident illumination is i_p while the d-c or ambient current is i_{dc}. This current is called the dark current. The noise current of the device is represented by i_N. Rs is the parasitic series resistance associated with the p material, Rp is a shunt resistance, and Cp is the shunt capacitance. These result from internal properties of the device. In the presence of a signal, Cp is modulated by the conductivity of the i-layer. At high light levels, the i-layer may be saturated and Cp may become quite significant. The result is a decrease in quantum efficiency and an increase in the rise time of the detector. The cut-off frequency (f_c) of the device is determined by Rs and Cp according to equation 1:

$$f_c = \frac{1}{2\ R_s C_p} \qquad (1)$$

The equation shows the limiting of the frequency response by R_s and C_p.

The pulser used in the system was commercially obtained and was designed for use with the laser diode. The pulser had an internal trigger circuit for use with pulse repetition frequencies (PRF) up to 600 HZ. It could also be configured for use with an external trigger such as the VCO square wave used in the system. In addition, its casing provided for mounting of the laser diodes and acted as a heat sink.

F. THE P-I-N SILICON PHOTODIODE DETECTOR

In conventional radio frequency receivers, an antenna receives the signal and passes it to a mixing circuit where the signal is demodulated from the carrier frequency to a frequency suited for further processing. The signal is then passed to further processing circuits. The photodiode detector performs the functions of the antenna and mixing circuit (or circuits).

The light transmitted by the laser consists of photons with energy, $h\nu$. The incident photons transfer their energy to electrons in the detector material. For wavelengths greater than about 1.2μ, the photons are not energetic enough to free an electron from the surface of the material; however, they produce an internal photoeffect which is the basis of the detection process.

A photoeffect is the result of interaction between photons and matter [Ref. 13]. The energy of the photon raises the electron from a nonconducting to a conducting state and, thereby, produces a charge carrier. The type of charge carrier is dependent upon the characteristics of the detector material. The material used as the detector with laser diodes is usually a semiconductor. If an intrinsic, or pure, semiconductor is used, the photon will produce an electron-hole pair. The pair production is

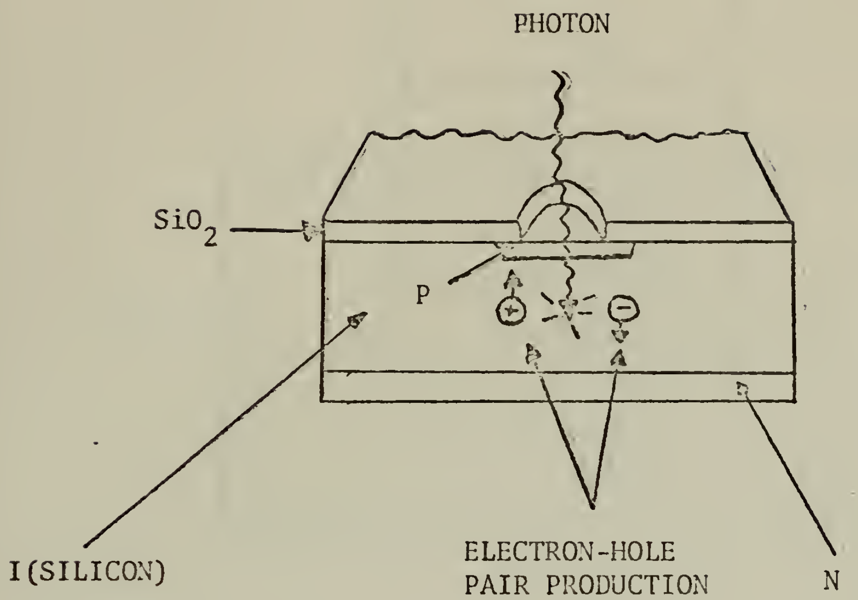


FIGURE 8: P-I-N PHOTODIODE

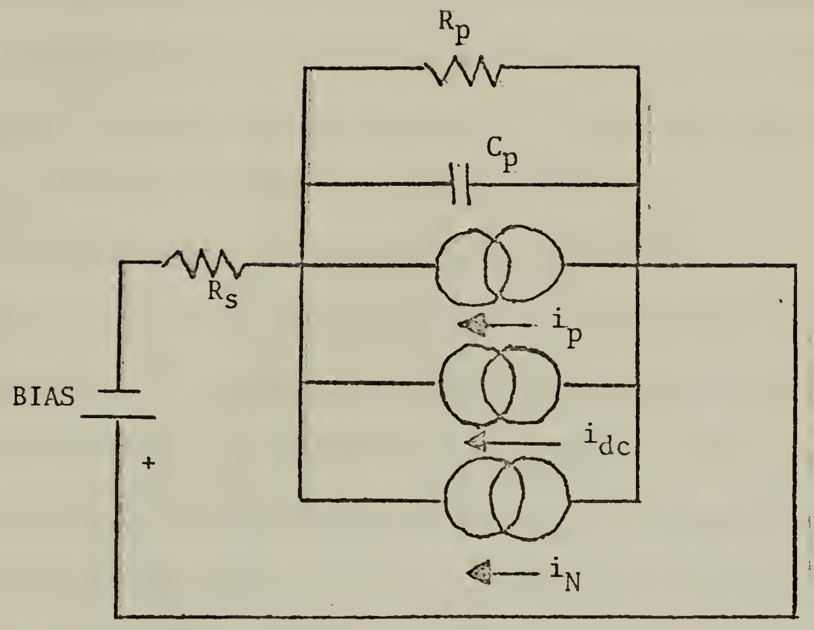


FIGURE 9: PHOTODIODE EQUIVALENT CIRCUIT (AFTER REF. 14)

R_S is determined by the thickness of the p-layer. The thinner the layer, the larger R_S is. Therefore, a design trade-off is made between the frequency response and conversion efficiency. C_p can be controlled by the applied bias.

The thickness of the i-layer is also controlled by the bias, with the higher the bias, the thicker the i-layer. Although photodiode detectors exhibit the highest detectibility when there is no bias [Ref. 13], the bias does have three beneficial effects. First, the electron-hole transit times are decreased; second, conversion efficiency is increased; and, third, the capacitance, C_p, is decreased [Ref. 14].

Since the current level produced by the photodiode is very low, external amplification is needed to produce a usable signal level. A low noise amplifier with high input impedance is required. In the system, a hybrid package consisting of the photodiode and an co amp operated in the current mode was used. The hybrid solved any interfacing problems in a package the size of conventional transistors. In operation, the photodiode acted as a light-controlled current source whose current flowed through an op amp feedback resistor to produce an output voltage. The feedback resistor was external to the package and selected to satisfy needs for gain and frequency response of the detector. Additionally, a bias voltage across a resistor was used to null out the dark current. The detector was selected to have its maximum response at the wavelength of the laser diode.

G. THE FREQUENCY DEMODULATOR

The output of the photodiode/op amp consists of pulses whose frequency is the same as the frequency of the transmitted signal. In order to reconstruct the original audio signal, the received FM signal must be demodulated. The audio signal modulated the VCO in the transmitter so that

the VCO output frequency corresponded to the magnitude of the audio input. This voltage must be extracted from the received signal. A PLL circuit was selected as the demodulator.

The block diagram of a PLL is shown in Figure 10. The PLL is a frequency feedback system comprised of four basic building blocks: a phase comparator, a low pass filter, an error amplifier, and a VCO.

The VCO operates at the free-running frequency f_o; this frequency for the FM system is the carrier frequency (7KHZ in the system). With the application of a signal, the phase comparator compares the frequency of the input, f_s, with the output of the VCO. The phase comparator is essentially a multiplier, which mixes the input signal with the VCO signal to produce the sum and difference frequencies, $f_s \pm f_o$. Two error voltages, $V_e(t)$'s that are related to the sum and difference frequencies between the two signals are generated. When there is no input signal, the error voltages are equal to zero. These voltages are then filtered to remove the sum frequency error voltage while the difference frequency error voltage is amplified and applied to the control terminal of the VCO. This control voltage, $V_d(t)$, forces the VCO to vary in a direction that reduces the difference in frequency. When f_o becomes sufficiently close to f_s, the feedback nature of the PLL causes the VCO to lock with the input. The PLL will then track the frequency changes of the input signal.

If the PLL is locked on a FM signal, the VCO tracks the instantaneous frequency of the input. The filtered error voltage, $V_d(t)$, which forces the VCO to maintain lock with the input signal, corresponds to the demodulated output. The PLL can be used for detecting either wide-band (high deviation) or narrow band FM signals with a higher degree of linearity than can be obtained by other detection means [Ref. 15].

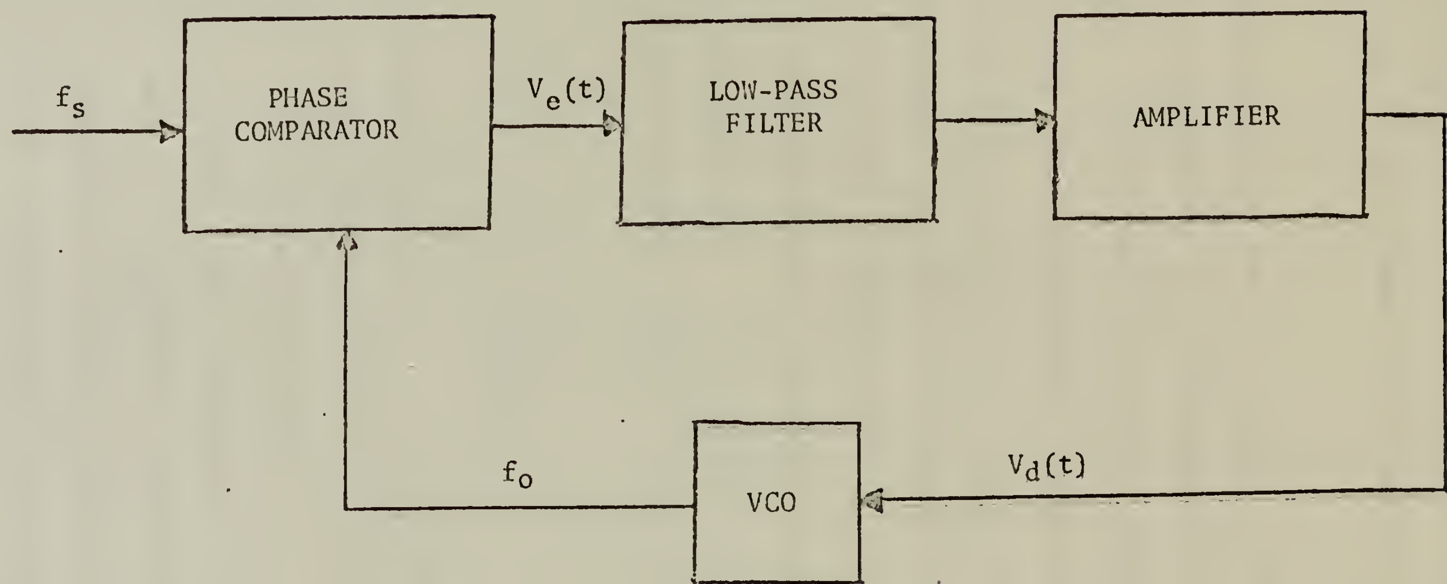


FIGURE 10: PHASE-LOCKED LOOP BLOCK DIAGRAM

The most critical block of the PLL is the VCO [Ref. 15] as frequency stability and FM demodulation characteristics of the system are normally determined by the VCO performance. The discussion of the VCO in the PLL applies to the VCO used in the transmitter as both are designed on the same principles.

The VCO is required to have the following properties: (1) linear voltage-to-frequency conversion, (2) good frequency stability, (3) high frequency capability, (4) high conversion gain, (5) wide tracking range, and (6) ease of tuning. The actual circuit of the VCO is shown in Figure 11. The circuit is an integrator-Schmitt-trigger combination. The timing capacitor C_1 is alternately charged and discharged by a voltage-controlled current source I_1. The Schmitt trigger senses the voltage level V_a across C_1 and turns the switch transistor T_3 off or on to initiate the charge and to discharge cycles respectively. The frequency of oscillation, f_o, can be expressed in the form given by equation 2 [Ref. 15]:

$$f_o = \frac{V_c g_m}{2C_1(V_2 - V_1)} \qquad (2)$$

where g_m is the transconductance of the voltage controlled current source, and V_2 and V_1 are the upper and lower trip levels for the Schmitt trigger. A square wave output can be obtained at node 1.

The PLL and VCO used were linear integrated circuits. The cost and complexity of PLL's were once considered a large obstacle to their use. The development of these types of PLL's in a monolithic circuit package has made the PLL usable in circuits such as the proposed laser FM system.

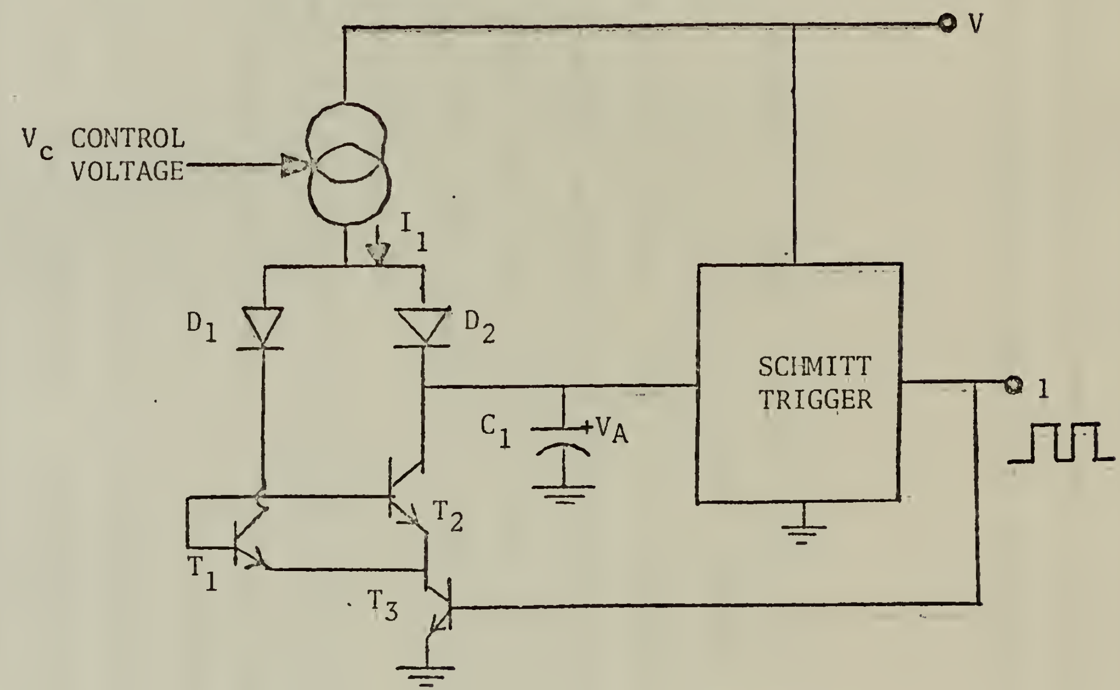


FIGURE 11: INTEGRATOR-SCHMITT-TRIGGER VCO

III. CIRCUIT DESIGN

Maximum use of integrated circuits (IC's) was made throughout the system wherever possible. With the exception of one IC used in the audio amplifier in the receiver circuit, all were made by the Signetics Corporation. The audio amplifier IC was made by the Radio Corporation of America (RCA).

A. TRANSMITTER

A microphonic amplifier is needed to amplify the audio signal from the microphone to a level that can be used to modulate the VCO. A Signetics PA239 was selected for this purpose. This IC is a low noise circuit which has two identically-matched amplifiers, each with 68 db gain. It is a high input impedance (250kΩ) device that permitted direct connection of a high impedance microphone. The output impedance is typically a 100Ω. The circuit used is shown in Figure 12.

A filter to pass the 300-3000 HZ band of frequencies was not designed, but its construction would have utilized active filter design similar to the filter used in the receiver (described in a later section). The voltage attenuator described in Section II also was not designed, but there are at least two ways to build these attentuators. One method uses an FET as voltage controlled resistance in a voltage divider circuit and a second method is an automatic gain control (AGC) circuit.

A typical voltage divider circuit is shown in Figure 13A. The maximum attenuation depends on the value of the drain-to-source resistance, R_{DS}, for a gate-to-source voltage equal to zero and on the source resistance R_S.

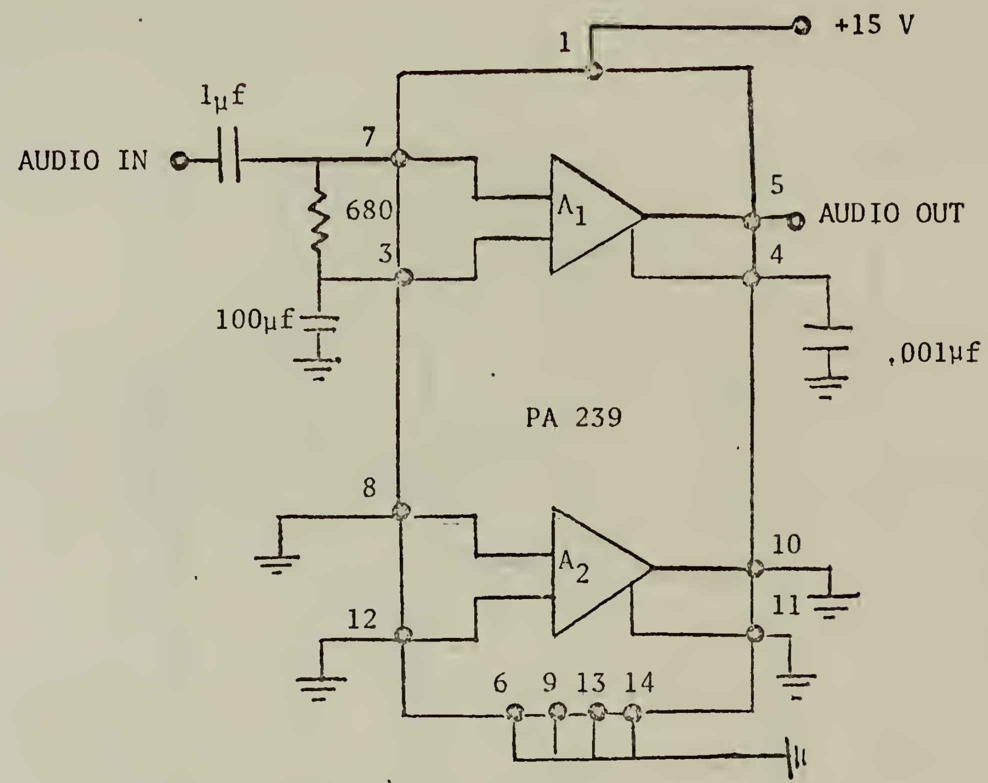


FIGURE 12: MICROPHONE PREAMPLIFIER

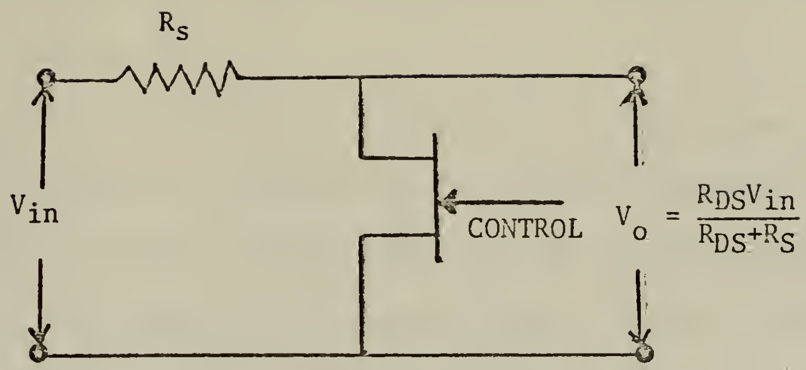


FIGURE 13A: FET VOLTAGE DIVIDER CIRCUIT
(AFTER REF. 17)

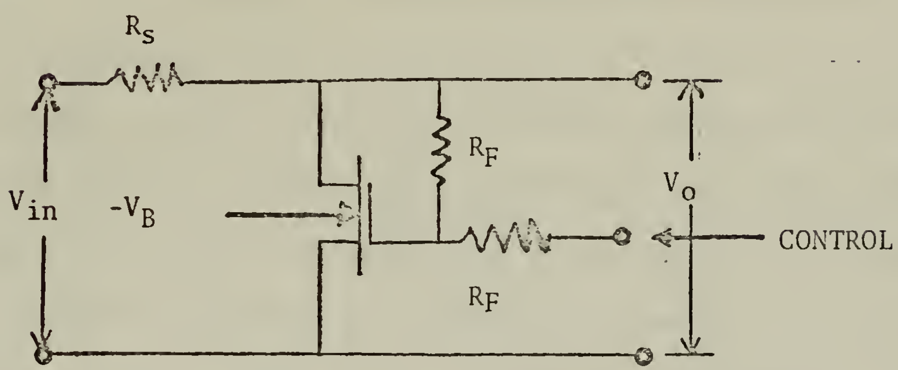


FIGURE 13B: VOLTAGE DIVIDER USING FEEDBACK
(AFTER REF. 17)

The range of attenuation that can be achieved is 0 to 20 or 30 db. A feedback arrangement can be used to avoid harmonic distortion from large input ac signals that may result in this circuit. A circuit using an n-channel MOS transistor is shown in Figure 13B. Other attenuator designs may be found in Ref. 17.

AGC circuits are usually used to control the output signal of audio amplifiers in receivers by compressing the voltage range of the input signals. Because of this limiting nature of AGC circuits, they could easily be used in the FM system to limit the modulating voltage to the VCO as described in Section II. The block diagram of an AGC circuit is shown in Figure 14. The input is fed directly to the control stage although a low-level amplifier may be used first for particularly weak signals. The operation of the control stage is usually accomplished by variation of the forward transfer characteristic of a transistor with the d-c bias current. Large input signals, however, usually have distorted outputs with this circuit and the AGC action is limited to about 20 db per stage [Ref. 18]. An example is shown in Fig. 15A. A second mode of operation is by variation of the dynamic resistance of a diode or transistor used as a two-terminal feedback or shunting element. Figure 15B is an example of this type of circuit. The input current divides between the diode resistance R_D and the input resistance of the amplifier. As the signal is increased, the AGC voltage increases, decreasing R_D as shown in Figure 16. This action limits the overall gain of this stage. For this type of AGC control, the signal source must have a high impedance and the input impedance of the amplifier must also be high [Ref. 18]. A typical power rectifier can consist of a half-wave rectifier and capacitance filter driving a dc amplifier (see Figure 17). Other AGC circuits are described in Refs. 19 and 20.

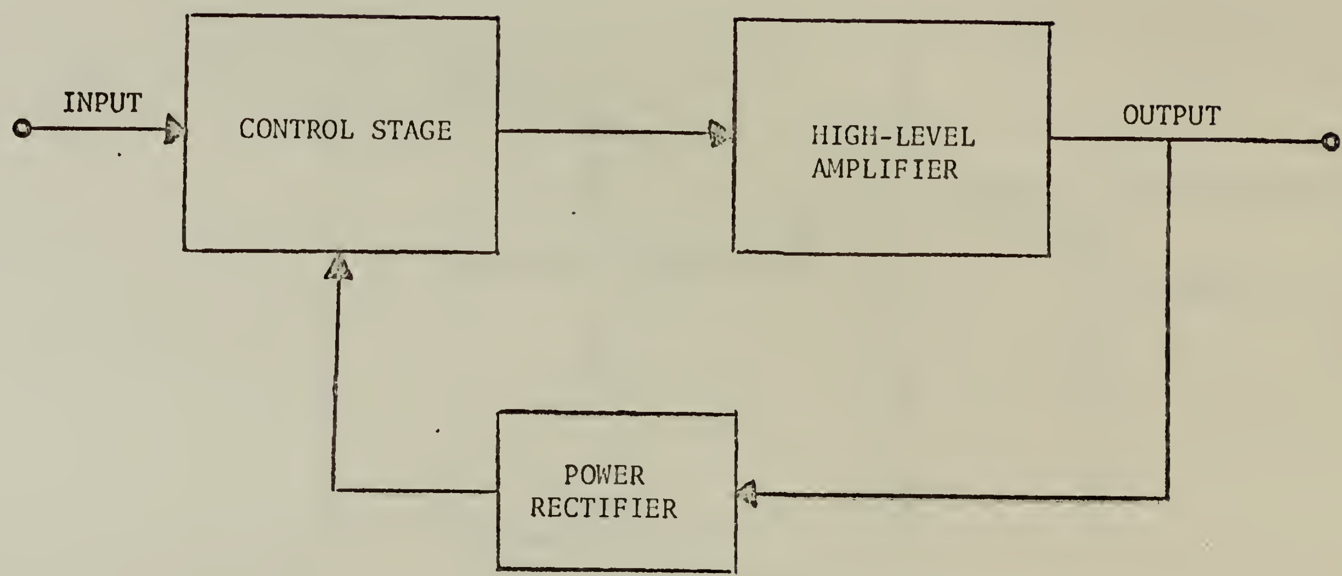


FIGURE 14: AGC BLOCK DIAGRAM

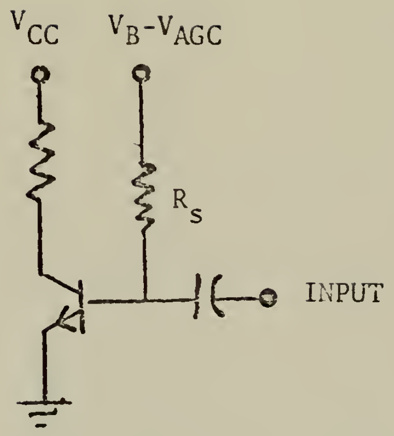


FIGURE 15A: AGC CONTROL CIRCUIT (AFTER REF. 18)

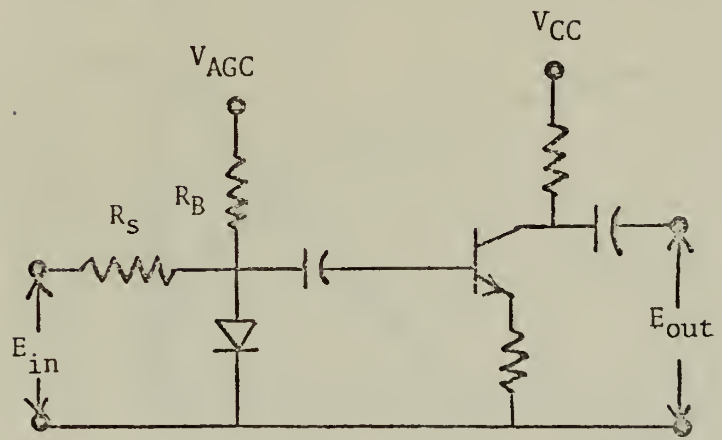


FIGURE 15B: AGC CONTROL CIRCUIT (AFTER REF. 18)

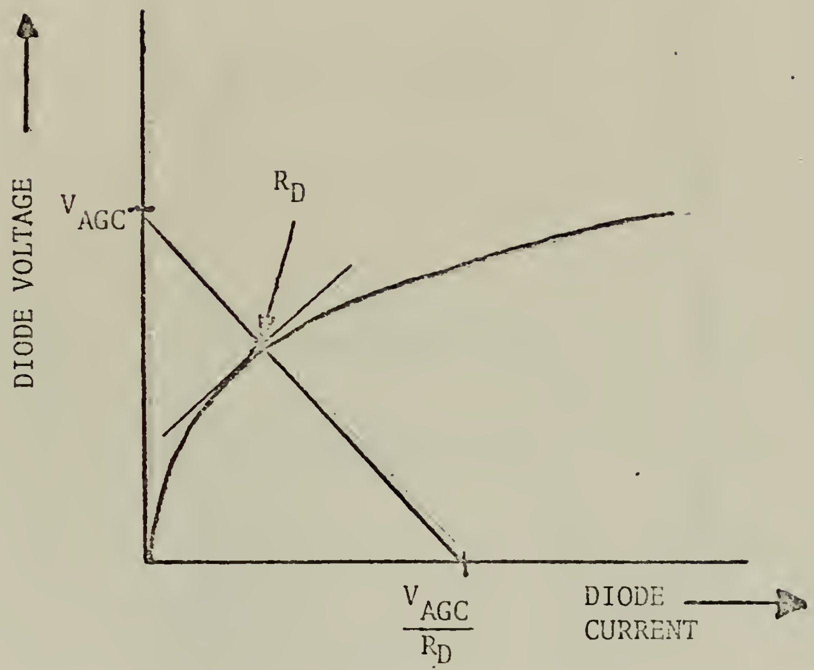


FIGURE 16: DIODE DYNAMIC RESISTANCE FOR CIRCUIT 15B

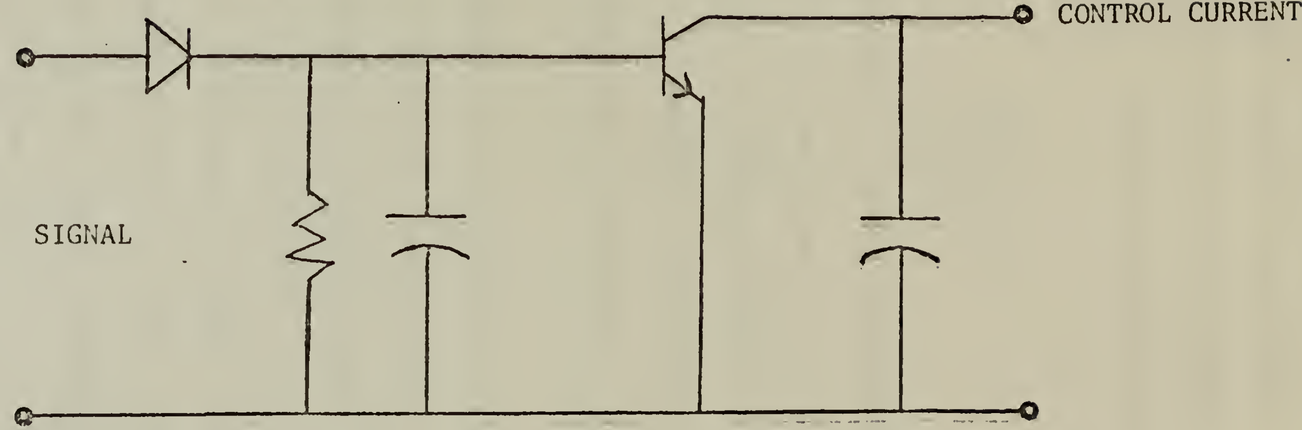


FIGURE 17: AGC POWER RECTIFIER (AFTER REF. 18)

The VCO was a Signetics NE566T, whose block diagram is shown in Figure 18A. The square wave output from pin 3 was used as the laser trigger voltage. The control terminal (pin 5) must be biased externally with a voltage V_c in the range $3/4\ v^+ \le V_c \le V^+$. The specification sheet of the 566 gives the square wave frequency as:

$$f_o = \frac{2(V^+ - V_c)}{R_1 C_1 V^+} \text{ HZ} \qquad (3)$$

The system VCO connection is shown in Figure 18B. V_c was set by the voltage divider formed with R_2 and R_3 and the modulating signal was ac coupled through C_2. R_1 was a variable resistor from 0 to 25 kΩ and used to select the free-running frequency of the system. A capacitor of .001μf was connected between pins 5 and 6 to eliminate any oscillations in the current control source.

The VCO transfer junction was obtained by using a variable dc voltage at pin 5. The transfer function is shown in Figure 19. The transfer function was needed to determine the maximum amplitude of the input to the VCO to give the desired ±1350 HZ modulation deviation. From the transfer function this voltage is ±.175v. and the input would have to be limited to this value by an attenuator as described above. The output impedance of the VCO is 50Ω and the VCO output could be directly coupled to the pulser trigger input as the pulser input impedance is approximately 60Ω.

The laser pulser and laser diode are manufactured by Laser Diode Laboratories and are designed for operation together. The pulser operation is described in Section II. The connection diagram is shown in Figure 20. For operation with the internal clock, terminals B and D are shorted together and a 58 v dc supply is connected to terminal C.

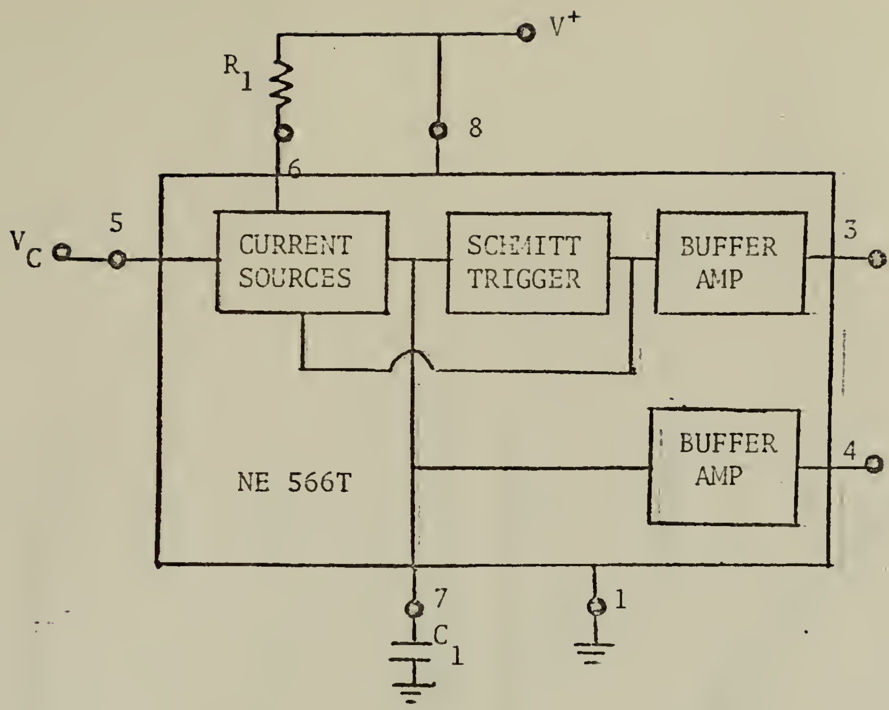


FIGURE 18A: SYSTEM VCO BLOCK DIAGRAM

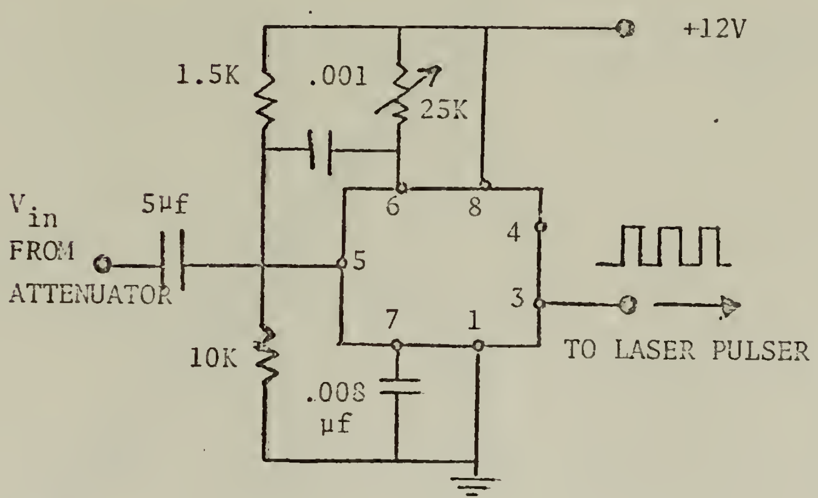


FIGURE 18B: VCO CIRCUIT CONNECTION

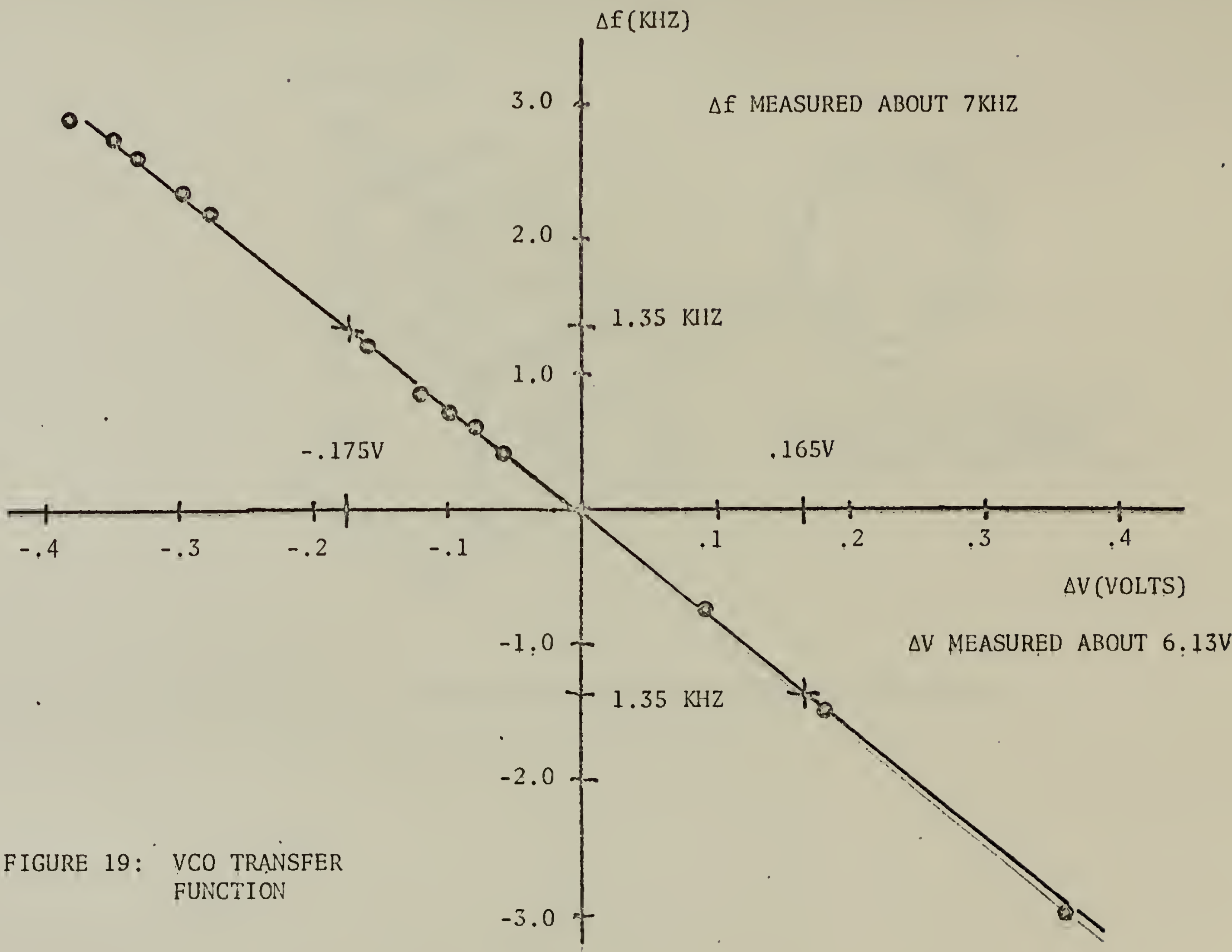


FIGURE 19: VCO TRANSFER FUNCTION

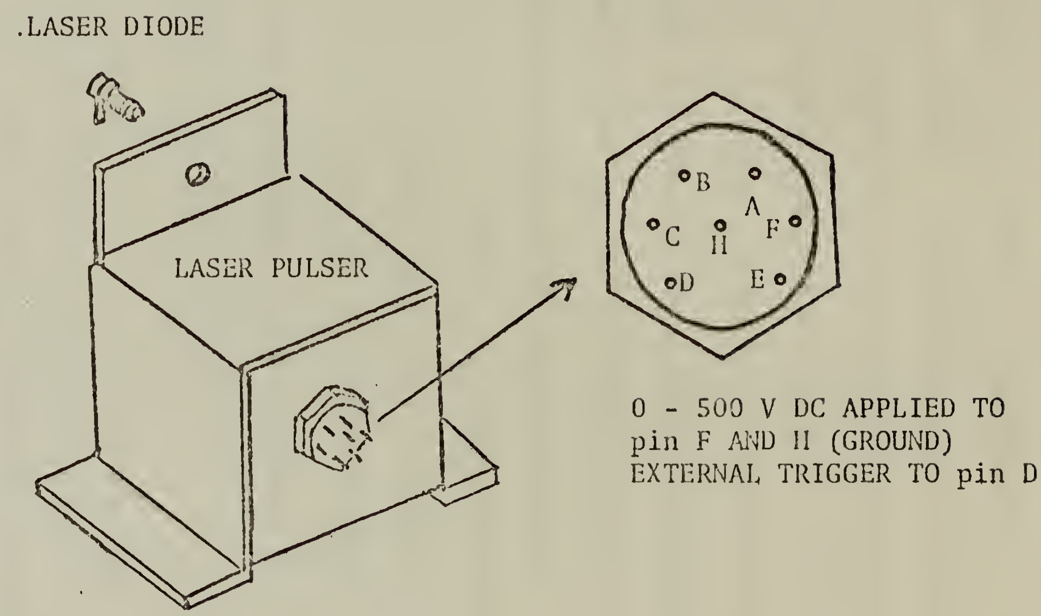


FIGURE 20: LASER PULSE SUPPLY CONNECTION

B. RECEIVER

The photodiode detector and op amp hybrid package (manufacturer's designation is UDT-400) discussed in Section II was manufactured by United Detector Technology with an active silicon detector area .10 inches in diameter. The electrical connection is shown in Figure 21. E_o equals the signal current from the photodiode (i_s) times a feedback resistor (R_f:0 to 10 MΩ). The resistor must be large for low light levels and small for high light levels. The bias voltage V_b is used for high speed as light and is variable from +15 to +50 V dc. The voltage and resistor combination at pin 1 is used for nulling out the dark current thereby improving detection capabilities by reducing background noise.

The PLL used as the FM demodulator was a Signetics SE 565 which was designed as a demodulator for the frequency range from .001 HZ (see Figure 22A) to 500 KHZ. The PLL can lock to and track an input signal up to $\pm.6$ of the VCO reference frequency. For the 7 KHZ reference, this is ±4.2 KHZ which means the PLL can track the FM signal which has a ±1350 HZ deviation. The system connection diagram is shown in Figure 22B. The VCO free-running frequency is given by equation 4:

$$f_o = \frac{1}{4\ R_1 C_1} \qquad (4)$$

C_1 was .01 μf and R_1 a variable resistor with maximum value of 25 KΩ permitting setting of the VCO to the exact frequency of the transmitter VCO. Pins 4 and 5 were shorted together to connect the VCO to the phase comparator. The demodulated signal is at pin 7. A .002μf capacitor was connected between pins 7 and 8 to eliminate oscillation in the control current source. A resistor may be connected between pins 6 and 7 to allow the lock range to

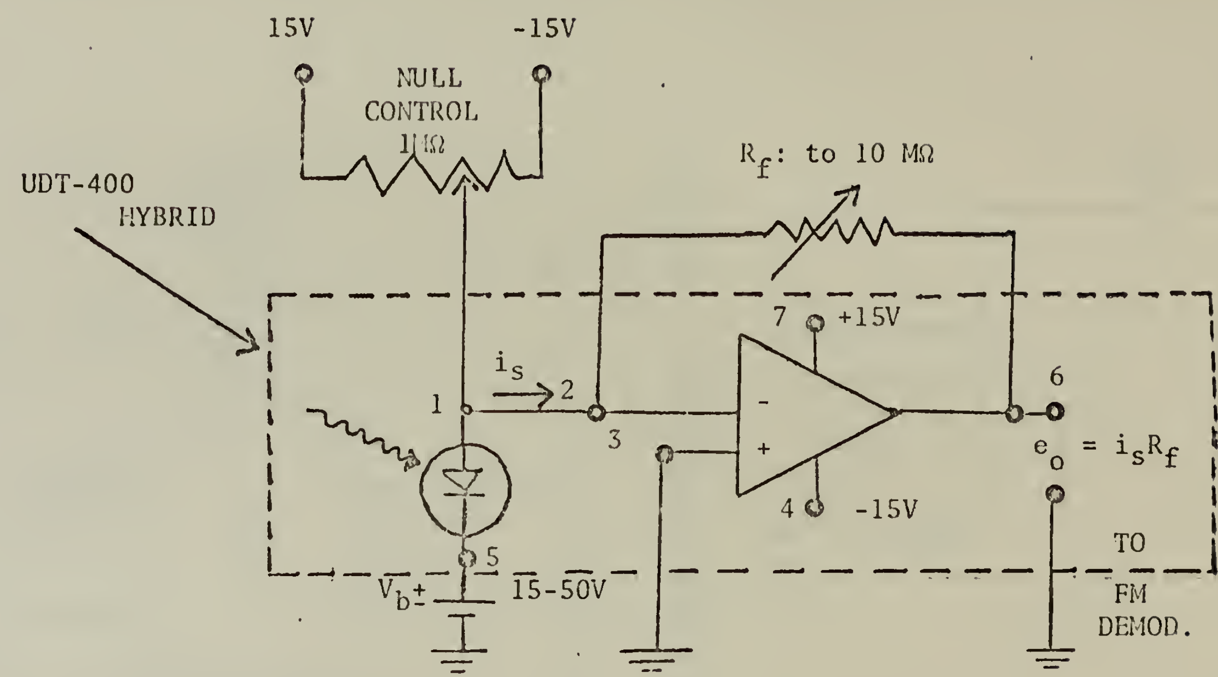


FIGURE 21: PHOTODIODE ELECTRICAL CONNECTION

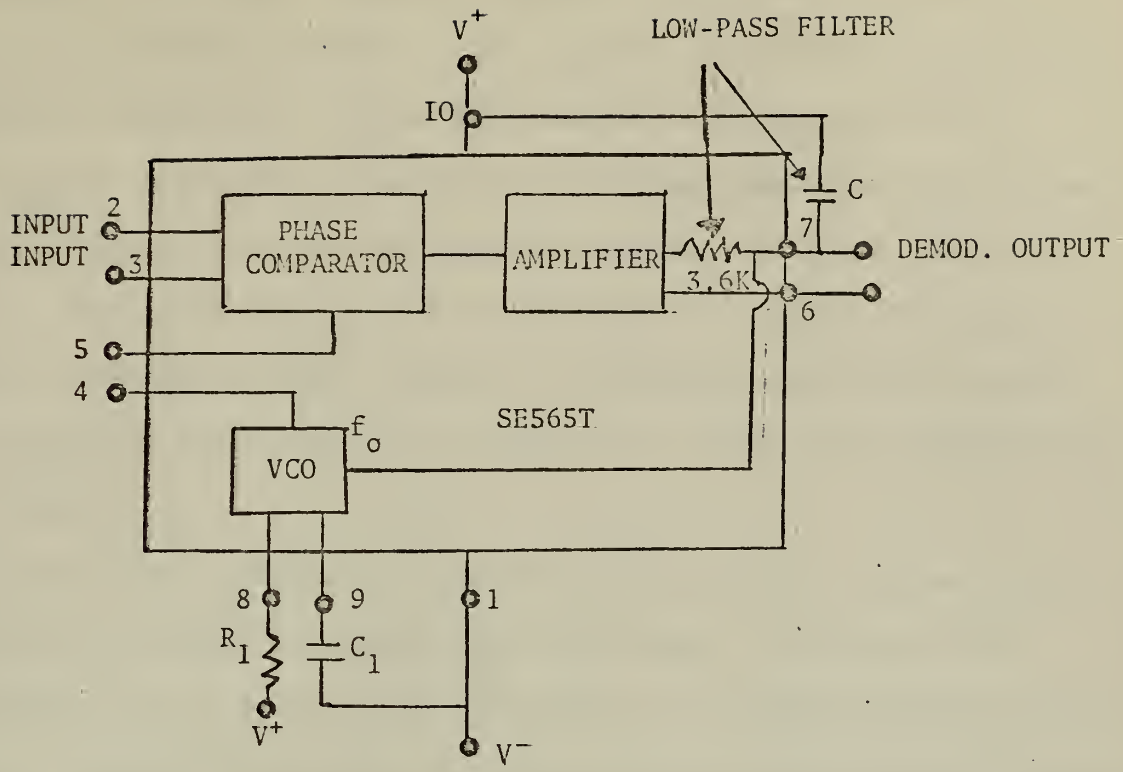


FIGURE 22A: SYSTEM PHASE-LOCKED LOOP BLOCK DIAGRAM

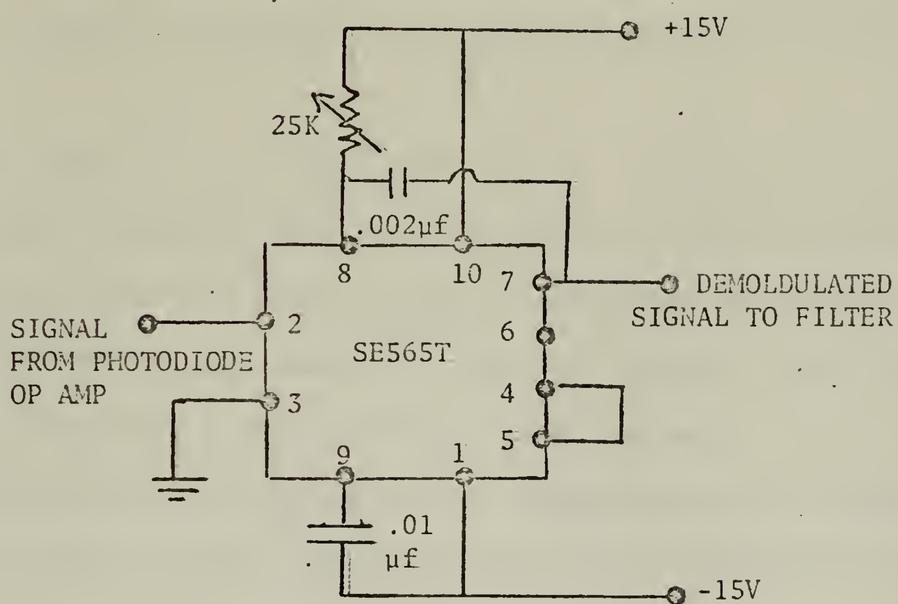


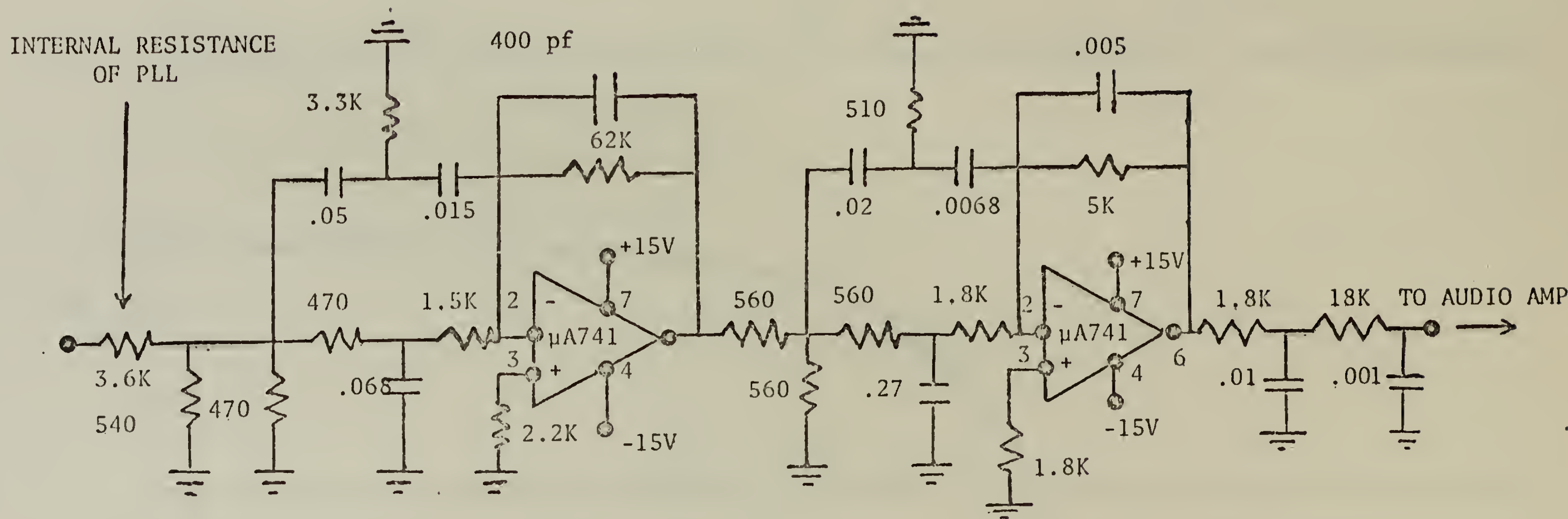
FIGURE 22B: PLL CIRCUIT CONNECTION

be decreased to ±.2 of the reference frequency. As shown in Figure 22A, the low-pass amplifier discussed in the operation of the PLL in Section II is formed by a capacitor C and the PLL internal resistance of 3.6 KΩ. However, in the system this capacitor-resistor combination was not used as the 7 KHZ signal was very strong and a filter with a notch at 7 KHZ was required. The output impedance of the photodiode is low while the input impedance of the PLL is high; therefore, an impedance match must be made in the connection between the two. A FET in the common drain configuration could be used.

The notch filter utilized was an active filter design using resistor-capacitor (RC) networks in combination with op amps. The usual active filter design uses at least one RC arrangement as a feedback network across the op amp and one RC combination in series with each input source to obtain a desired frequency response. The op amp stages can then be cascaded to realize most transfer functions. References 21-23 present a few of the many possible methods of synthesizing transfer functions using active filters.

The filter used in the system was done by the synthesis of the transfer admittance after a design in Ref. 24. The circuit is shown in Figure 23. Components were selected to give a notch at 7 KHZ about 50 db below the response in 300-3000 HZ pass band. The frequency response curve is shown in Figure 24. Signetics μA741's were used as the op amps.

A RCA CA 3020 audio IC used to drive a complementary pair of power transistors provided the audio amplification of the demodulated signal. The circuit is shown in Figure 25. The IC is direct coupled to the output stage, which delivers power to the speaker in a transformerless configuration. This configuration can deliver power output up to 3.3 watts at a total harmonic distortion of 10% into an 8Ω speaker load [Ref. 25].



ALL CAPACITANCES ARE μf
EXCEPT AS NOTED.

FIGURE 23: 7KHZ NOTCH FILTER

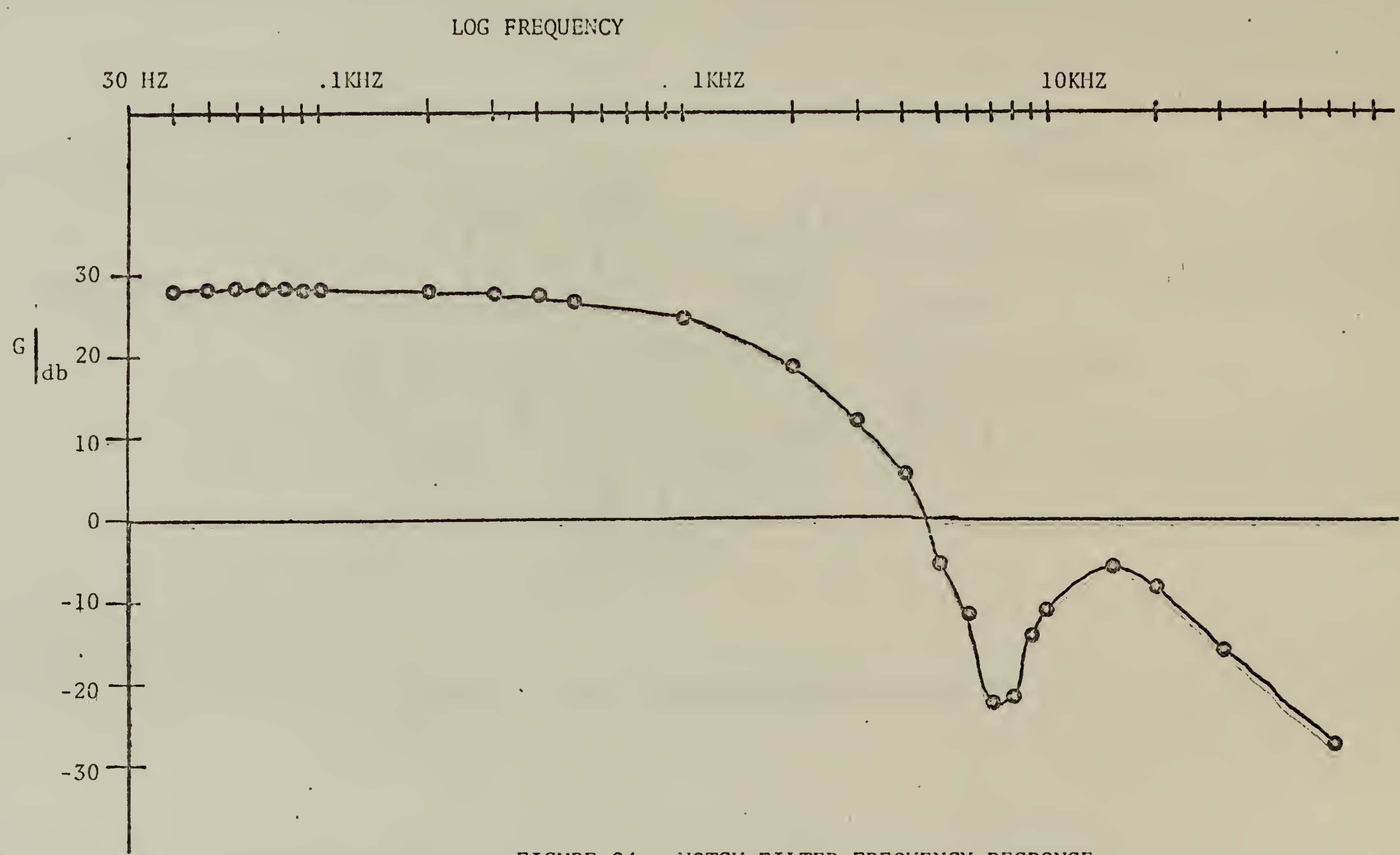


FIGURE 24: NOTCH FILTER FREQUENCY RESPONSE

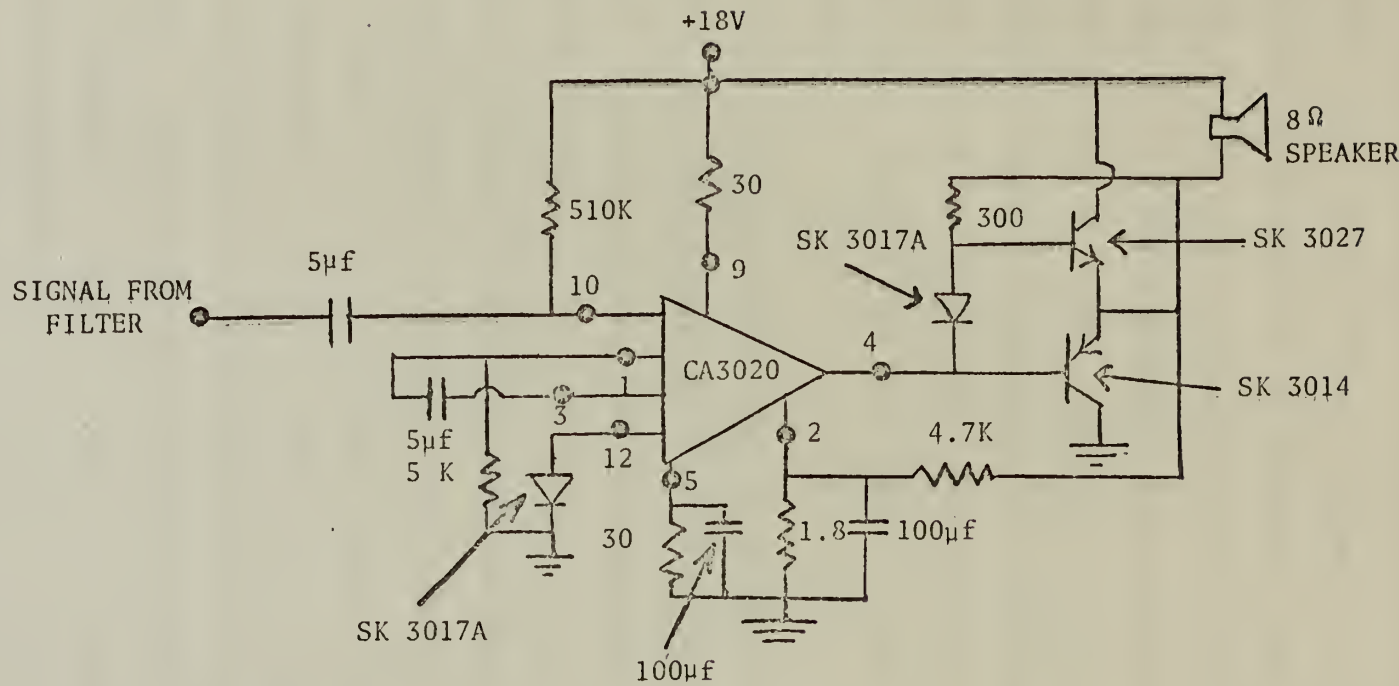


FIGURE 25: AUDIO AMPLIFIER CIRCUIT (AFTER REF 25)

IV. CONCLUSIONS

The complete system did not work at a rate greater than 1 KHZ, short of the carrier frequency of 7 KHZ. The problem was first noticed when the photodiode output fell off from a maximum at 1 KHZ to the point where it disappeared in the noise of the detector at about 2 KHZ. The problem was believed at first to be the failure of the photodiode/op amp combination to respond to the higher frequency light pulses although its rated frequency response extended to 10 MHZ. The pulser was the investigated and a research of its specifications revealed that its maximum pulsing capability with an external trigger was only 1 KHZ. Unfortunately, this fact was not discovered until too much time had elapsed to get or build a suitable pulser to replace it.

The proposed operation for the system was a valid design. Individual blocks of the system were designed and built with the exceptions of the bandpass filter and attenuator in the transmitter circuit. The VCO functioned properly and, in a test, was modulated by a sine wave. The signal was applied electrically to the demodulator and the PLL output was the input (modulating) sine wave. The need for a filter circuit resulted from the above test when a sine wave signal in the band from 300 HZ to 3000 HZ was used to modulate the VCO, and the output of the PLL failed to be the sine wave due to distortions produced by the 7 KHZ carrier and its harmonics. The filter produced the desired notch at 7 KHZ and roll-off at higher frequencies as shown in Figure 24. The audio amplifier and speaker combination converted sine wave signals into audio tones with some squelch noted. This problem can be corrected by a better socket connection for the

audio IC and by fixed mounting of the speaker. The main problem to be corrected is the pulser and this can be accomplished by the design or purchase of a suitable laser pulser which must be capable of operation up to 10 KHZ, about the maximum PRF for the laser diodes used.

The use of integrated circuits was believed important. These IC circuits provide for portability of the system due to their small sizes and power requirements which can be supplied by batteries. Their ruggedness reduces susceptibility to damage, and low cost keeps the overall system price low. The VCO has exceptional stability and linearity, and the PLL provides a means of FM demodulation with a higher degree of linearity than can be obtained with the use of conventional FM detectors.

V. SUGGESTIONS FOR FURTHER STUDY

Although the complete system did not work it should be relatively easy to get a working communicator once the pulser circuit is replaced. Transceiver configuration can be the next step in further design. The use of IC's should make this stage of the design quite easy. To add to the portability of the system, pulser supplies can be built that operate from a battery supply.

Optical lenses could be added with the purpose of increasing the range of the system by focusing the beam. In addition, this optical work could be conducted with the idea of increasing the security of the system. A very narrow beam would be less likely to be intercepted than a broad beam and could be directed at the receiver with the knowledge that the receiver would be the only one detecting the transmission. Suitable filters for the receiver optics would suppress any background noise from sunlight and other light sources.

By replacing the laser diode with a LED, the system could be used as the transmitter and receiver in a fiber optics system. Operation would remain the same but power requirements would be reduced considerably. The LED can also be used at much higher PRF's than the laser, thereby utilizing more of the bandwidth of the infrared spectrum. This would enhance adaptation of the system to multiplexing, permitting many channels to be transmitted by the light.

A secure network for ship-to-ship communication could be developed utilizing the laser, due to the invisibility of the infrared emission to

the eye and due to the directivity of the beam. This system could replace the present bulky voice-coded cryptographic systems in use. The IC construction gives portability and makes maintenance easier while greatly reducing the size of the equipment.

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13. ABSTRACT

The design of a system for point-to-point voice communications using a frequency modulated diode laser as the transmitter is presented. Theories are discussed for the Ga-As semiconductor laser, the laser pulse circuits, the p-i-n silicon photodiode detector, and the frequency demodulator. Designs of the elements of the system and some experimental results are presented. Operation of a complete system is discussed.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Pulse Frequency Modulated Laser						
Voice Frequency Use						
Phase-Locked Loop Demodulator						

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